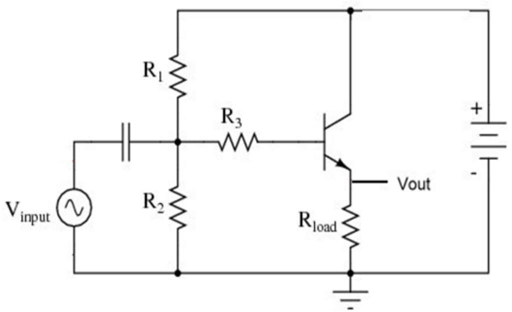
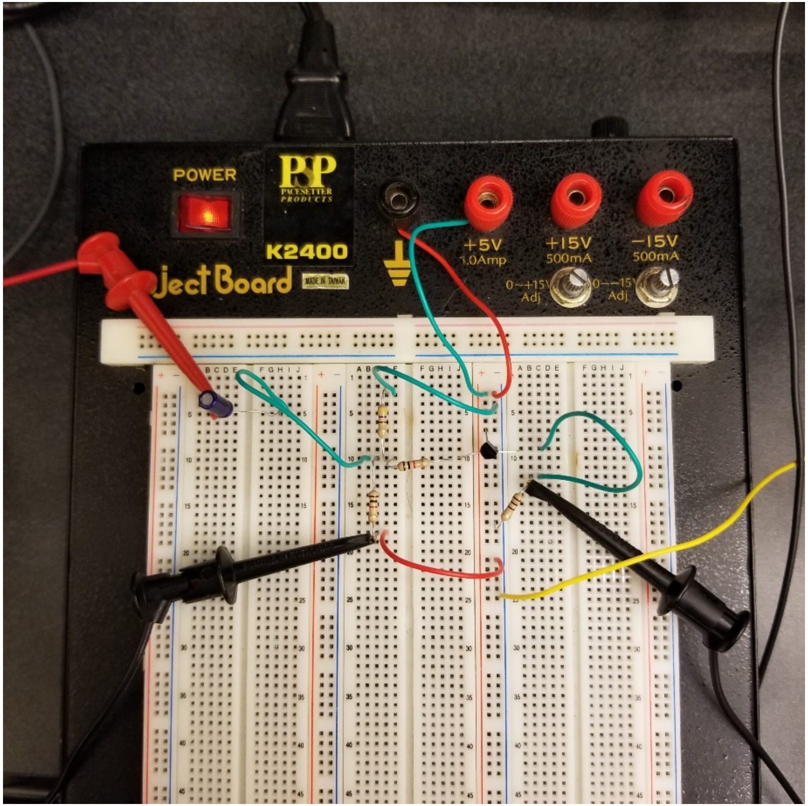
Avoiding Circuit ~~Mistrakes~~ Mistakes



(1) Does the protoboard circuit look like the circuit diagram?

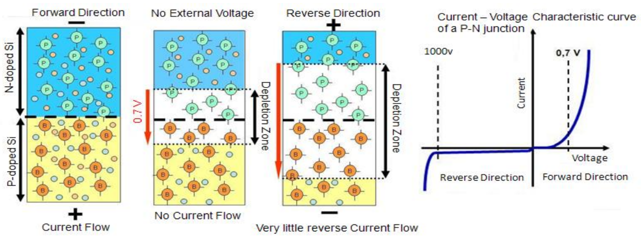
(2) Is the wiring simple and easy to troubleshoot?



Review Semiconductors

- **Semiconductors**
  - **Resistivity (ρ), R= ρL/A**
    a material property
  - **Si, GaAs, InN, CdTe**
    <valence>=4 bonding electrons
- **Doping in Semiconductors**
  - **Donor, *n*-type conduction**
    to the right in periodic table
  - **Acceptor, *p*-type conduction**
    to the left in periodic table
  - **ρ=1/*ne*μ**, μ=mobility, σ=1/ρ
- ***pn*-Junction Diode**
  - Depletion Region **narrows** in forward bias
  - Depletion Region **widens** in reverse bias
- **Transistors**
  - **2 diodes**
  - **Bias the base input**

II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg				



Questions ?

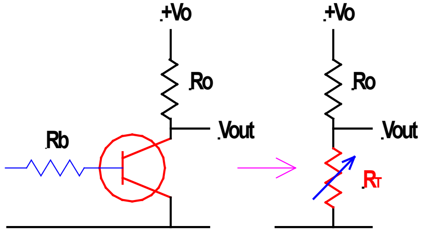
Review Transistors

- **Transistors**
  - Bipolar Junction Transistor – npn, pnp
  - **Base-controlled variable resistor**
  - **Use as Voltage Divider circuit**
  - Regimes:

cut-off R → large

linear R → finite

saturated R → small



$$V_{OUT} = V_0 \left(\frac{R_T}{R_T + R_0} \right)$$

Any Transistor

- **Base-controlled VARIABLE RESISTOR**
- **Use in a VOLTAGE DIVIDER circuit**

Review Transistors

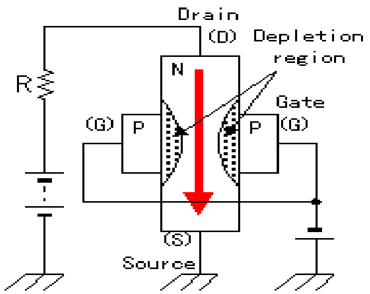
- **FET – Field Effect Transistor**

  $R = \rho L/A$

  Area changes by electric field via applied voltage
  - 99.9999+ % of all transistors

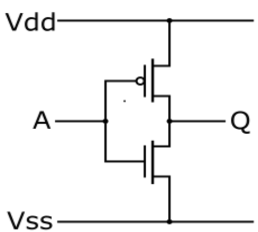
- **MOSFET** - Metal Oxide Semiconductor FET

- **CMOS** - Complementary MOS



MOSFET

Oxide layer prevents current into the gate

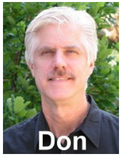


CMOS

One FET is always **off**,
the other FET is always on.
No current flows to ground when off.

Questions ?

Electronics - PHYS 2371/2



Calendar of Topics Covered

Physics PHYS 2371/2372, Electronics for Scientists

Don Heiman and Hari Kumarakuru

Northeastern University, Fall 2020

Also see **Course Description** and **Syllabus**

This is a schedule of the topics covered, but it may be modified occasionally (10/02/2020).

Week #	**Lectures**	**Weekly Topics** (Chs.)	**Homework** (Ch-Problem)	**Lab Experiments** (always look for latest version)
IV Sept 30-Oct 2	**Wed Lecture** Semicond pdf Semicond video	Solid State Devices (Ch-40) *p-n* Junction Diodes (Ch-41) Transistors/Circuits (Ch-42-45)	HW Handout	**Worksheet-4** Worksheet-4 video ***Say Hello (and Goodbye) to the Transistor***
V Oct 7-9	**Wed Lecture** Operational Amplifiers	Op-Amp Basics (Ch-28, 31) Basic Op-Amp Circuits (Ch-29)	28-1/3/4, 29-1/2/3/4	**Lab-5, *Op-Amps***
VI Oct 14	**Wednesday** Study for EXAM-1	**Study for EXAM-1** **Basics, AC Circuits, Semiconductors, Op-amps**		No Lab
VII Oct 19, 21-23 **MON/WED**	**MONDAY EXAM-I**	**Wed Lecture** Magnetoelectronics Magnetic induction/flux Transformers (Ch-11)	11-all	**Lab-6, *Build a Magnetometer***

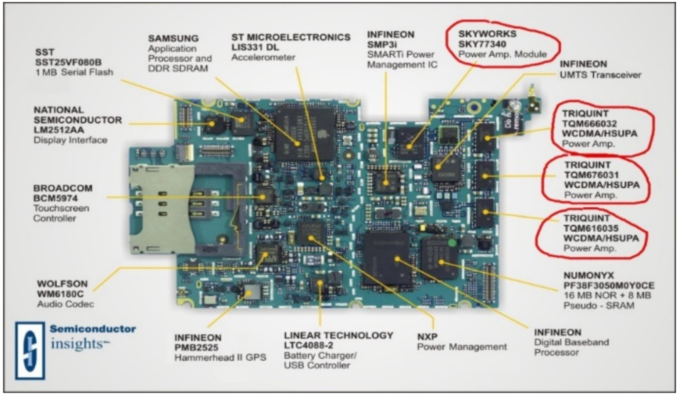
TODAY

Op-Amp Basics, Ch. 28

Op-Amp Circuits, Ch. 29

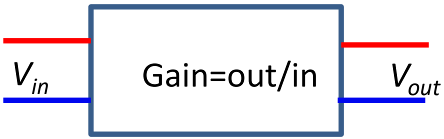
- ☐ **Why Op-Amps?**
  - Linear amplification
  - Much easier to configure
- ☐ **Golden Rules**
  - Simple way to design Gain
- ☐ **What can we do with Op-Amps?**
  - Noninverting amplifier
  - Voltage follower
  - Current-to-voltage converter
- ☐ **Do Math with Op-amps**
  - Simple summing amplifier
  - Difference amplifier
  - Differentiator
  - Integrator

Amplifier Uses for Op-Amps



Linear Amplifier

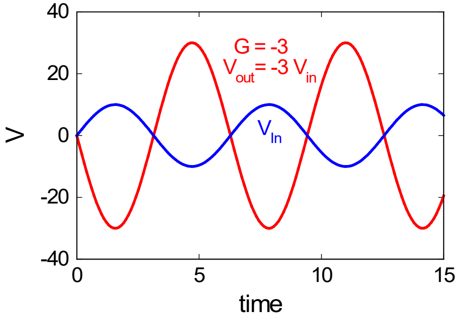
Amplifier
4-terminal device
Negative or positive output



Amplify
Voltage, Current, Power

Voltage Gain
$G_V \equiv V_{out} / V_{in}$

- $G_V >> 1$, e.g. $G_V \sim 10^5$
- $G_V = 1$, unity gain (current gain)
- $0 < G_V < 1$, *attenuator*
- $G_V < 0$, e.g. $G_V = -3$, inverting



Gain in Decibel Units

Decibels

dB units

Voltage Gain

$G_V = 10^{dB/20}$

dB=20 log(G_V)

Power=**V**^{2}/R

Power Gain

$G_P = 10^{dB/10}$

dB=10 log(G_P)

Voltage Gain

G_V	dB
10^{-2}	-40
1	0
10	20
100	40
1000	60
10^4	80
10^5	100
10^6	120

Power Gain

G_P	dB
10^{-2}	-20
1	0
10	10
100	20
1000	30
10^4	40
10^5	50
10^6	60

Questions ?

History of Operational Amplifiers

Negative feedback

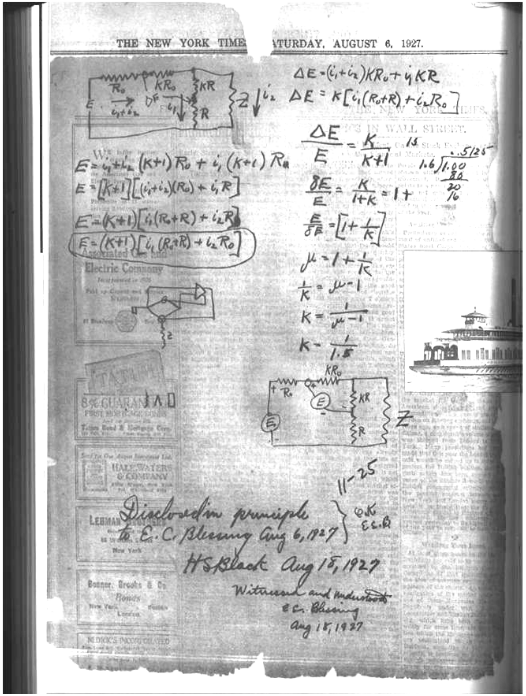
Negative feedback is required for
self-regulation or to control the Gain

1927: Negative feedback
Harold Black first developed negative feedback principles as a passenger on the ferry (from Hoboken Terminal to Manhattan) on his way to work at Bell Laboratories. (see article)

1930's: Negative feedback amplifier
Harold Black, Paul Voigt, Alan Blumlein, B.D.H. Telleg

1941: A vacuum tube op-amp
Patented by Karl D. Swartzel Jr. of Bell Labs
Contained vacuum tubes to achieve a gain of 90 dB
Used in WW II radar system

1947: An op-amp with an non-inverting input
First defined in a paper[15] by John Ragazzini of Columbia U
A footnote mentioned a 2-input op-amp design
by a **student** Loebe Julie.
First op-amp to have inverting and non-inverting inputs.



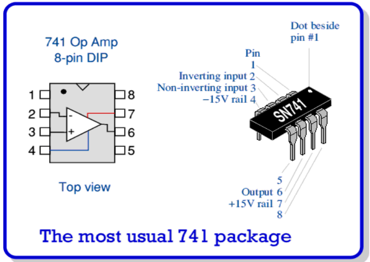
Operational Amplifier (Op-Amp)

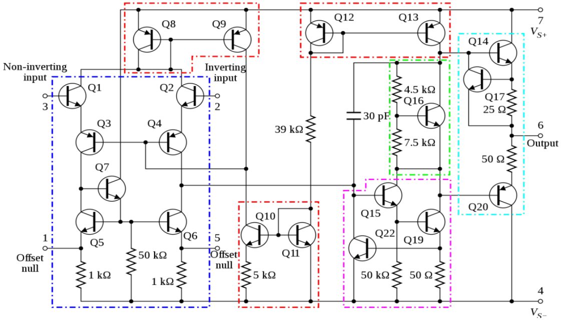
Semiconductor Op-Amp
Invented in 1966
at Fairchild Semiconductors

741 General purpose op-amp (1968)

Integrated circuit contains
20 transistors
11 resistors
1 capacitor

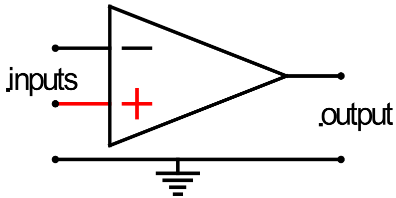
Many Youtube videos
www.youtube.com/results?search_query=op+amp





What does the **output circuit** look like?

Op Amp or Op-amp



Two inputs

Noninverting (+)
Inverting (-)

As V_{in} increases
Noninverting: V_{out} increases
Inverting: V_{out} decreases

Differential Inputs

V_{out} goes **positive** or **negative**

$V_{out} = G\,(|V_+| - |V_-|)$

For $V_+ > V_-$, $V_{out} > 0$ (pos)

For $V_+ < V_-$, $V_{out} < 0$ (neg)

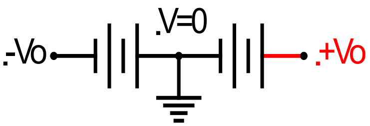
Example, G=10

If $V_-=1$ V, $V_+=0$ V
$V_- > V_+$
then $\mathbf{V_{out} = -10\ V}$

If $V_-=0$ V, $V_+=1$ V
$V_+ > V_-$
then $\mathbf{V_{out} = +10\ V}$

Questions ?

Power Supply for Op-Amp

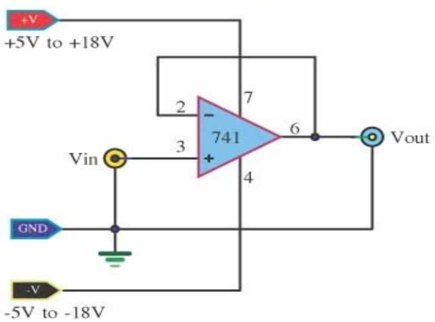


Dual Supply

Needs a dual voltage supply

$+V_o$ and $-V_o$ (also called V_{cc})

The power supply is usually
not shown in the circuit



Cannot get more V_{out} than the power supply V_o

Example, G = 10^5

$V_- = 1$ V, $V_+ = 0$ V
$V_{out} \sim -V_o$ (supply voltage)

$V_- = 0$ V, $V_+ = 1$ V
$V_{out} \sim +V_o$ (supply voltage)

Questions ?

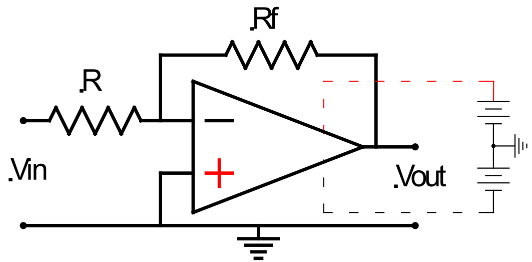
Simple Circuit: **Ideal inverting amplifier**

R_f = feedback resistor

- puts part of the output on inverting (-) input

Question: What happens if you put part of the output on the noninverting (+) input? (positive feedback)

Answer: output saturates to maximum voltage (like a *microphone in front of a speaker*)

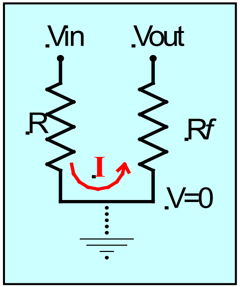


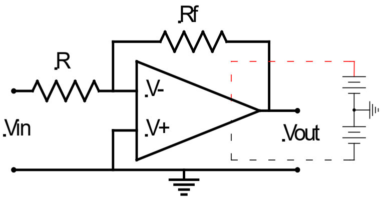
Compute Op-Amp Circuit Gain

Golden Rules

1. **Assume op-amp input voltages are equal**
   - *Virtual Ground Approximation*
2. **Assume no current flows into op-amp inputs**
   - *Infinite Impedance Approximation*

Op-amps are designed so that the output adjusts ***automatically*** *to make the 2 op-amp input voltages equal.*





Note:
Current is toward V=0 for R
Current is away from V=0 for R*f*

This gives V_{in} and V_{out} ***opposite signs*** *and* ***G is negative***.

Apply Rule-1 : if $V_+=0$ then $V_-=V_+=0$ (at ground)

Apply Rule-2 : No currents flow into op-amp (ground)

$I_R = I_{Rf} = I$ assume current CCW

Now, $V_{in} = I_R R$ assume V_{in} is positive
and $V_{out} = -I_{Rf} R_f$ since I direction is reversed

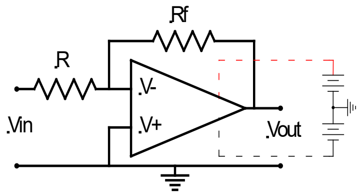
$I = V_{in}/R = -V_{out}/R_f$
so $V_{out} = -V_{in} (R_f/R)$
and Gain=V_{out}/V_{in} → **$G_o = - R_f / R$**

Basics of Opamp circuits (0-2:50)

Questions ?

Nominal versus **Real** Op-Amp Gain

- **Nominal** Gain, **G_o**, from Golden Rules
- **Real** Gain, **G**, is what the circuit provides
- **Open loop** Gain, **A**, what the op-amp can provide



$G_o = -R_f/R$ nominal gain

$$G = \left(\frac{-R_f}{R}\right)\frac{A}{A+(R_F/R)+1}$$ real gain

A = open loop gain (~10^5)

Prob. 28-2

Given R=10 kΩ and R_f=1 MΩ,
compute nominal gain G_o, real gain G and error
for open loop gains of A=10, 10^3, and 10^6.

Use $G_o = -R_f/R$ as nominal or closed loop gain.
G_o = - 1 MΩ/10 kΩ = **-100** *nominal gain*
Real gain is $G = G_o A/(A+(R_f/R)+1)$

Real gain divided by nominal gain
For A= 10, $G/G_o = 10/(10+100+1)$ = **10/111**
For A= 10^3, $G/G_o = 10^3/(10^3+100+1)$ = **1000/1101**
For A= 10^6, $G/G_o = 10^6/(10^6+100+1)$ = **1,000,000/1,000,101**

Error = 100% $[(G - G_o)/G_o]$ = 100% $[G/G_o - 1]$

741 Op-Amp Device Characteristics

~ skip

Open Loop Gain $A_V = 10^5$, 100 db

V_{out} = A ΔV = A (V_+ - V_-) →

Input Impedance (draws some current)

741 ~ 2 MΩ

FET op-amp ~ 10^{12} Ω

Input Offset Voltage (741 has V_{offset} ~ 2 mV)

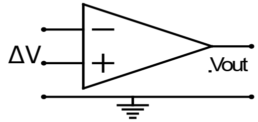
Gives $V_{out} \leq G^*V_{offset}$ →

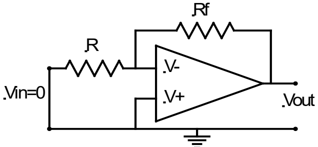
Input Bias Current (741 ~ 0.1 μA)

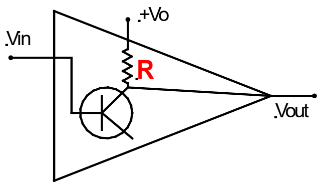
Output Impedance (741, R ~ 75 Ω, 20 mA) →

Slew Rate = $dV/dt]_{max}$ (741, ~ ½ V/μs)

How fast V_{out} can be changed







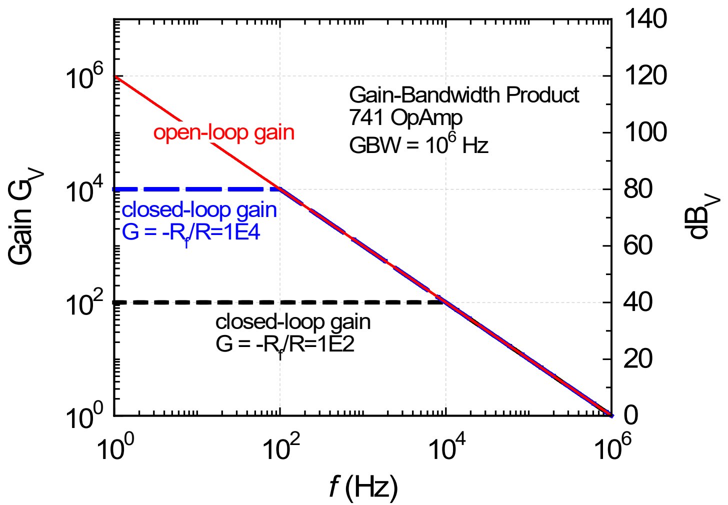
741 Frequency Response

Gain-Bandwidth Product

$$G * f_{max} = \text{constant} = 10^6 \text{ Hz}$$

If gain is large,
cannot amplify high *f*.

If you want high *f*,
need to keep gain low.



Questions ?

Things you can do with an Op Amp

Better Inverting Amplifier

Noninverting Amplifier

Voltage Follower

Current-to-voltage Converter

Simple Summing Amplifier

Difference Amplifier

Differentiator

Integrator

skip

Better Inverting Amplifier

Noninverting Amplifier

Voltage Follower

Current-to-voltage Converter

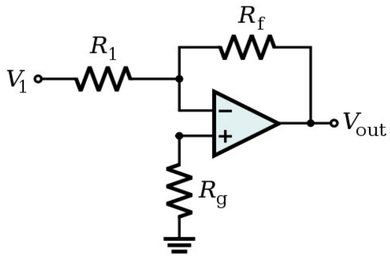
Simple Summing Amplifier

Difference Amplifier

Differentiator

Integrator

Eliminate input bias current

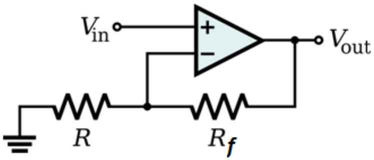


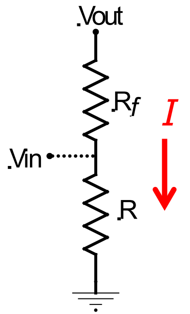
$$G = -R_f / R_1$$

$$\frac{1}{R_g} = \left(\frac{1}{R_f} + \frac{1}{R_1 + R_{source}} \right)$$

- Better Inverting Amplifier
- **Noninverting Amplifier**
- Voltage Follower
- Current-to-voltage Converter
- Simple Summing Amplifier
- Difference Amplifier
- Differentiator
- Integrator

Positive in
Positive out





$$I_{R_f} = I_R = I, \quad \text{since } I_- = 0$$

$$V_{in} = IR, \quad \text{since } V_{in} = V_- = IR$$

$$V_{out} - V_{in} = IR_f$$

$$V_{out} = V_{in} + V_{in}\left(R_f / R\right)$$

$$G = V_{out} / V_{in} = R_f / R + 1$$

skip

Better Inverting Amplifier

Noninverting Amplifier

Voltage Follower

Current-to-voltage Converter

Simple Summing Amplifier

Difference Amplifier

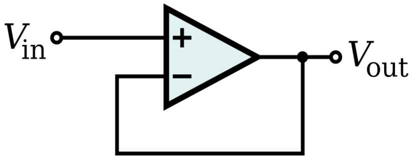
Differentiator

Integrator

Unity gain
Buffer (current) amplifier
High Z_{in}, Low Z_{out}

High Z_{in} implies low current ($I_{in} \sim V/Z_{in}$)

Low Z_{out} implies high current ($I_{out} \sim V/Z_{out}$)



$V_{in} = V_+$

$V_{out} = V_-$

$V_{in} = V_{out}$

$G = 1$

skip

Better Inverting Amplifier

Noninverting Amplifier

Voltage Follower

Current-to-voltage Converter

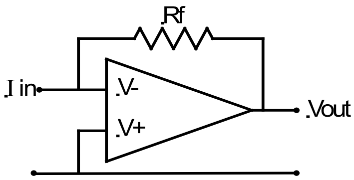
Simple Summing Amplifier

Difference Amplifier

Differentiator

Integrator

Current In
Voltage Out



$V_+ = 0, \; V_- = V_+$

$I_{in} = I_{Rf}$

$\mathbf{V_{out} = -I_{in} R_f}$

Better Inverting Amplifier

Noninverting Amplifier

Voltage Follower

Current-to-voltage Converter

Inverting **Summing** Amplifier

Difference Amplifier

Differentiator

Integrator

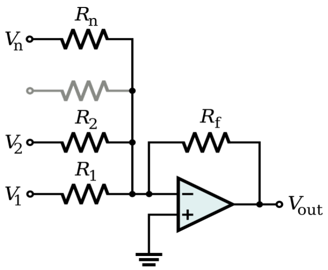
Use Op-amps

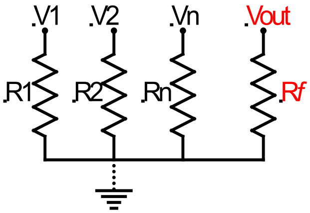
to do **MATH !**

They can even do calculus

Add voltages

- Better Inverting Amplifier
- Noninverting Amplifier
- Voltage Follower
- Current-to-voltage Converter
- **Inverting Summing Amplifier**
- Difference Amplifier
- Differentiator
- Integrator





$$V_{out} = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2 ...... - \frac{R_f}{R_n}V_n$$

$$For\ R_1 = R_2 ...... = R_n = R$$

$$V_{out} = -\frac{R_f}{R}(V_1 + V_2 ...... + V_n)$$

skip

"Differential Amplifier"

Better Inverting Amplifier

Noninverting Amplifier

Voltage Follower

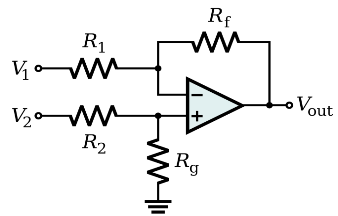
Current-to-voltage Converter

Simple Summing Amplifier

Difference Amplifier

Differentiator

Integrator



$$I_+ = I_- = 0, \; V_+ = V_-$$

$$For \; R_1 = R_2 = R, \; R_g = R_f$$

$$V_+ = V_2 \frac{R_f}{R + R_f}$$

$$\frac{V_{out} - V_-}{R_f} = I_{Rf} = I_{R1} = \frac{V_- - V_1}{R_1}$$

$$Let \; V_- = V_+ \; and \; substitute \; for \; V_+$$

$$V_{out} = \frac{R_f}{R}(V_2 - V_1)$$

Read Wikipedia
for $R_1 \neq R_2$ and $R_g \neq R_f$
http://en.wikipedia.org/wiki/Operational_amplifier_applications

Time-derivative of Voltage

dV_{in}/dt

Better Inverting Amplifier

Noninverting Amplifier

Voltage Follower

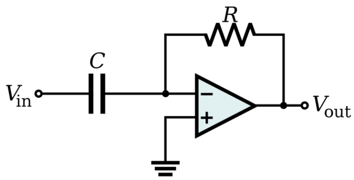
Current-to-voltage Converter

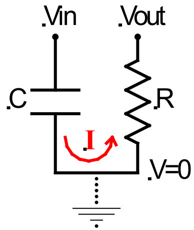
Simple Summing Amplifier

Difference Amplifier

Differentiator (inverting)

Integrator





$$V_{+} = 0, \quad \text{since grounded}$$
$$V_{-} = V_{+} = 0$$
$$I_R = I_C = I, \quad \text{since } I_{-} = 0$$
$$C = Q / V \; or \; Q = CV$$
$$I_C = \frac{dQ}{dt} = C\frac{dV_{in}}{dt}$$
$$I_R = -V_{out} / R = C\frac{dV_{in}}{dt}$$

$$V_{out} = -RC\frac{dV_{in}}{dt}$$
$$V_{out} = -\tau\frac{dV_{in}}{dt}$$

Again τ = RC
units of time (s)

For a sine wave
<G> = ωτ

Questions ?

Time-integration of Voltage

$\int V_{in} dt$

Better Inverting Amplifier

Noninverting Amplifier

Voltage Follower

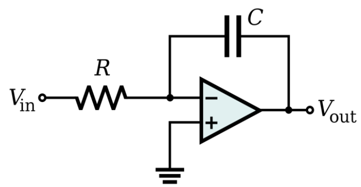
Current-to-voltage Converter

Simple Summing Amplifier

Difference Amplifier

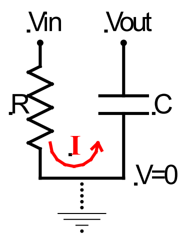
Differentiator

Integrator (inverting)



$$V_{out} = -\frac{1}{RC}\int_0^t V_{in}\,dt$$

$$V_{out} = -\frac{1}{\tau}\int_0^t V_{in}\,dt$$



$V_- = V_+ = 0$ since grounded

$I_C = I_R = I$ since $I_- = 0$

$V_{in} = IR$

$$Q = CV_{out},\quad I = \frac{dQ}{dt} = -C\frac{dV_{out}}{dt}$$

$$I = V_{in}/R = -C\frac{dV_{out}}{dt}$$

$$\int\left[\frac{1}{RC}V_{in} = -\frac{dV_{out}}{dt}\right]dt$$

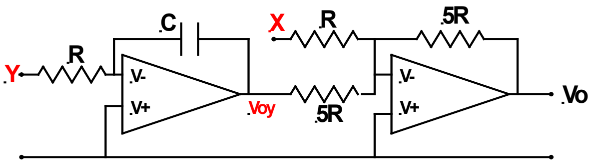
Again τ = RC
units of time (s)

For a sine wave
<G> = 1/ωτ

Questions ?

Homework Example (Ch. 29)

Given the circuit, write the equation.



Begin with the voltages X and Y.

The output voltage from the right hand op-amp is

$$V_{0X} = XG_X = X(-\frac{R_f}{R}) = X(-\frac{5R}{R}) = -5X.$$

The left hand op-amp is in an integrator circuit,

so $V_{out} = -\frac{1}{RC}\int V_{in}dt$ for that op-amp.

Then at point $V_{0Y} = -\frac{1}{RC}\int Ydt$, where Y is the input voltage.

V_{0Y} is then input in the right hand op-amp,

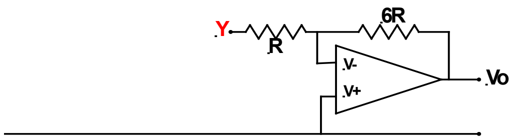
so V_{0Y} is multipled by the right hand gain $G = -\frac{5R}{5R} = -1$

to give $\left(-\frac{1}{RC}\int Ydt\right)(-1) = \frac{1}{RC}\int Ydt.$

The total output is now $V_0 = -5X + \frac{1}{RC}\int Ydt$

Questions ?

Homework Example, Ch. 29



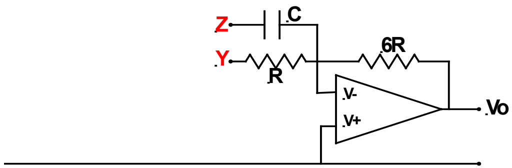
Given the equation, draw the op-amp circuit.

The given output voltage is $V_o = +4X - 6Y - 3\,{dZ}/{dt}$.

X, *Y* and *Z* are voltages

Begin with the voltage Y since that term is negative.

Draw an inverting amplifier with $G_Y = -6$, using R and $R_f = 6R$.



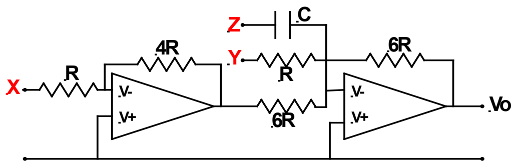
You need a differentating circuit for Z,

so add a capacitor C to the input of that op-amp.

For a differentiator $V_{out} = -RC\,{dV_{in}}/{dt}$.

You need an output of $-3\,{dZ}/{dt}$,

and since $R_f = 6R$, then $6RC = 3$ or $C = {1}/{2R}$.



Finally, you need a 4X output.

Add a second op-amp on the left with $G_{1X} = -4$, using R and $R_f = 4R$.

Output this V=-4X into the right hand inverting op-amp

with $G_{2X} = -1 = -\frac{6R}{6R}$.

Thus the output from X is $V_{oX} = G_{1X}G_{2X} = (-4X)(-1) = +4X$.

Questions ?

Lab Experiment – 5

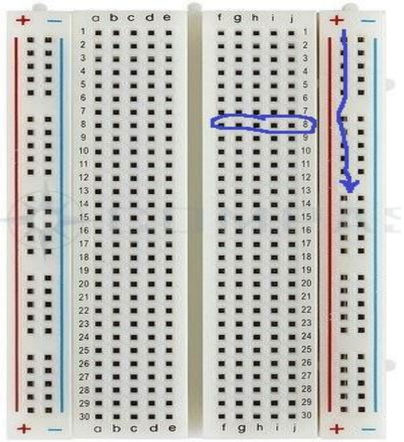
Op-Amp and Circuits

Don't forget to power the chip with
+12 V and –12 V or
+15 V and –15 V

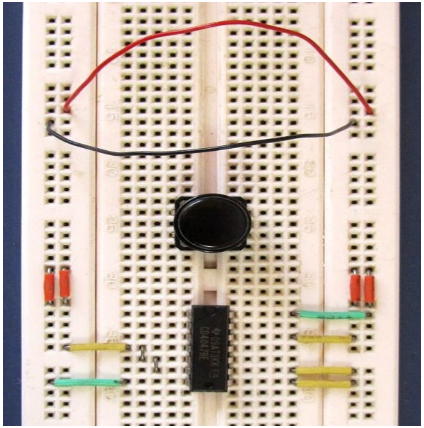
Use the power supply **ground**
as the ground for the
input (V_+ or V_-) and the output (V_{out}).

We are here to help
Please
- **ask lots of questions in the lab**
- **come to Zoom on Monday**
- **email questions to TA or me**

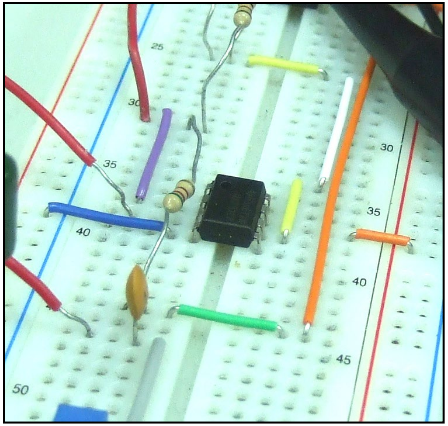
Protoboard (breadboard) Wiring



The 5-hole rows are connected horizontally. The long red/blue rows are connected vertically.



Typical layout with voltage on the long vertical rows.



741 op-amp circuit

Lab-5, Op-Amps and Circuits

Physics PHYS 2371/2372, Electronics for Scientists
Don Heiman and Hari Kumarakuru, Northeastern University

I. Op-amp Basics

Connect $+V_o$, $-V_o$ (~ ±15 V) to power the 741. Don't mistake the power supply voltages ($+V_o$ and $-V_o$) with the inputs denoted as V_+ and V_- in textbooks.

1. What is V_{out} when +5 V is applied to the inverting input?
2. What is V_{out} when +5 V is applied to noninverting input?
3. Why does the output voltage saturate near the supply voltages?
4. What is the maximum output current that the 741 can supply?
5. What is the maximum power a 741 can deliver to an 8 Ω speaker?

II. Frequency Dependence

III. Differentiator Circuit

IV. Integrator Circuit

V. Summary

Written Lab Report is required.

See the report Template.

Please

- read the instructions before the lab

- visit the Monday discussion section

종료